JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 39, No. 5, September–October 2002

Gore/Seam Architectures for Gossamer Structures

C. H. Jenkins*
South Dakota School of Mines and Technology, Rapid City, South Dakota 57701
and
W. W. Schur†
NASA Wallops Flight Facility, Wallops Island, Virginia 23337

Gossamer spacecraft are ultra-low-mass (areal densities <1 kg/m^2) structures with applications in communications, imaging, and propulsion. Often large, for example, diameters greater than 10 m, aperture architectures can be either filled (monolithic) or sparse (segmented). Although filled apertures provide the greatest performance, manufacture of large monolithic, that is, seamless, apertures is extremely challenging. Gore/seam architectures provide a compromise for fabrication of gossamer spacecraft. Segments (gores) are manufactured and then assembled into a continuous aperture by seaming together the gores. A similar process was chosen for the Inflatable Antenna Experiment and has been used for decades in the fabrication of large high-altitude scientific balloons. The architecture options for design and fabrication of gossamer spacecraft are reviewed, with particular emphasis on precision applications in communications and imaging. The near-term inevitability of seaming as a fabrication method is emphasized, and the point of view is taken of using seams to advantage. The possibility of "active seams" to mitigate some of the aforementioned issues is discussed and extended to go further to find other uses for the active seams. Lessons learned from NASA's high-altitude balloon program are reviewed in improving structural integrity through use of novel gore/seam design.

Introduction

TECHNOLOGY developments that enable future space missions may well fall into two broad categories: those that enable very large spacecraft (gossamer spacecraft) or very small spacecraft (micro- and nanospacecraft). Certain science missions, in imaging, communication, and power, for example, will only be realized with large aperture configurations (greater-than-20-m diam). Because of essentially fixed launch mass allowables, as craft become larger, their mass per aperture area (areal density) must come down.[1] Hence, current gossamer spacecraft (GS) tend to be composed of thin polymer or other films, with considerable multifunctionality built in.

The only tried and flight-tested method of fabricating GS currently available is to seam together smaller sections of film (gores); this was the method used on Echo and the Inflatable Antenna Experiment (IAE). Spin casting of films has been used to create GS ground-test articles; however, the challenges in spin casting monolithic films greater than 20 m in diameter are daunting to say the least. Certainly, other concepts for fabrication will arise, for example, in situ manufacturing in space. However, in the near term (and likely for some time to come), seaming together gores remains the viable alternative for GS fabrication.

Gore/seam design still presents many challenges, including 1) fabrication issues, that is, bonding, stress transfer, and added weight; 2) performance issues, that is, stiffness mismatch, strain mismatch, slope discontinuity, and wrinkling; and 3) the durability issue, that is, bonding.

An additional challenge for any method of GS fabrication is the special requirements of precision gossamer apertures (PGAs). Stringent requirements on isotropy and homogeneity of material properties and on surface smoothness at large and small length scales, among others, make extra demands on any fabrication process. In the context of PGAs, the problems with seams are many, including that they represent nonuniform, discontinuous stiffness, leading to inevitable strain mismatch and undesirable surface topology (Fig. 1).

Moreover, to achieve apertures that are large, PGAs must be packaged compactly during launch and then deployed on orbit. As the IAE experiment has taught us, requiring reliable deployment alone is quite challenging by itself. Requiring reliable deployment and precision of the onorbit shape simply compounds the challenge, especially when some form of adaptivity is expected. Usually, precision of shape requires small adjustments of the aperture's surface, whereas deployment from the stowed to the gossamer size requires enforcing deformations that are orders of magnitude larger than the thickness of the membranelike aperture.[2]

This seemingly impossible contradiction can be circumvented in the present concept by allowing the active deployment and precision elements to function somewhat independently while sharing the same locations at the seams. In fact, locating the deployment and precision elements at the seams provides unique opportunities for integrating them together, at least spatially, just as the bones and tendons of a bat together deploy the wing and keep the skin aerodynamically configured (Fig. 2). In this scheme, opportunities for locating actuators and sensors at the seams, and for implementing cooperative or independent controls, also exist.

There is a great tradition of partitioning structural function in structural design. Common examples are separating the tension and compression carrying functions 1) in a concrete beam to steel reinforcement and concrete, respectively, or 2) in a sailboat to guy wires and masts, respectively. NASA's high-altitude scientific balloon program has used the gore/seam architecture to advantage by partitioning the global and local load carrying functions to the load tapes and gores, respectively.

Active Seams

We desire to exploit novel architectures in gore/seam configurations of precision gossamer apertures as a means of enabling their realistic fabrication, deployment, and control. Even though such architectures appear natural, seaming in the past has been suffered as an unfortunate necessity. On the other hand, constructing a large monolithic aperture, with a precisely shaped and seamless surface, will be extremely expensive and difficult.

We suggest a new paradigm that looks to exploit the opportunities that seams present while mitigating their deficiencies. The approach

Received 5 July 2001; revision received 13 December 2001; accepted for publication 29 April 2002.

*Professor, Compliant Structures Laboratory Mechanical Engineering Department; Christopher.Jenkins@sdsmt.edu. Member AIAA.
†Research Engineer, Physical Sciences Laboratory, willi.w.schur.1@gsfc.nasa.gov. Member AIAA.

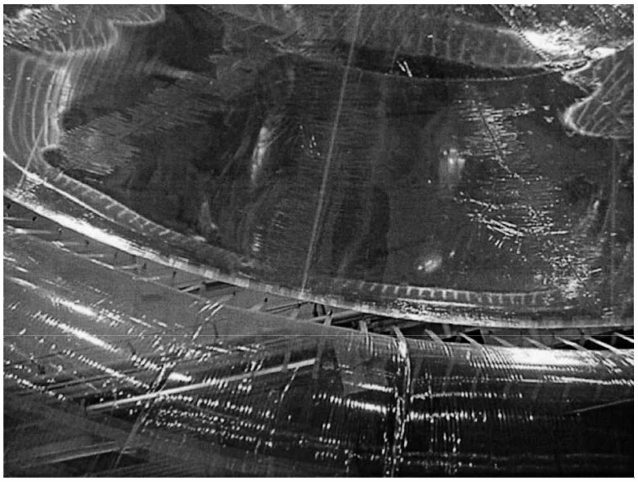

Fig. 1 Detailed view of the interconnection between aperture and support torus on a 10-m SRS Technologies reflector; wrinkling along aperture seams, as well as torus, is evident.

Fig. 2 Fruit bat showing wings constructed of a thin skin stretched over a stiff substructure.

proposed herein promises to enable greater mission capabilities by constructing more precise optical surfaces at less cost. Missions that can benefit from this technology include ultralightweight large apertures for optical, infrared, and submillimeter telescopes, "photon buckets" for optical communications and noncoherent imaging for the detection of extrasolar planets, solar concentrators for power generation, and radio frequency antennas for Earth observation.

A number of possibilities must be examined, including 1) achieving greater adaptability to deployment and eliminating the need for inflation; 2) integrating sensor, actuators, and power supply; and 3) providing more authority for precise surface control.

Preliminary results indicate that uneven heating of the membrane surface may significantly degrade performance,[3] which provides merely one example of the need for active shape control. Because large-scale PGAs will perform in extreme environmental conditions, the materials selected to control actively their shape and stability must satisfy stringent design requirements in terms of resisting tear, ultraviolet degradation, etc. Active polymers hold great promise as sensors and actuators in the control scheme, due to their light weight and packageability.

At present, considerable attention is focused on the development of advanced electroactive polymers for aerospace and other technological applications.[4] The potential for low weight, flexibility, stable piezoelectric properties, and high sensitivity to mechanical loads of these materials provides significant promise for active shape and position control of flexible structures. At present, polyvinylidene fluoride (PVDF) is the only commercially available piezoelectric polymer considered suitable for active sensing and control. Other active polymers have emerged and are currently being investigated in terms of their potential and effectiveness for an expanded range of applications. In particular, novel piezoelectric polyimides have been recently developed at NASA Langley Research Center with new improved performance characteristics at elevated temperatures. An active research program at the Jet Propulsion Laboratory (JPL) is focused on the use of ionic polymers as sensors and actuators.

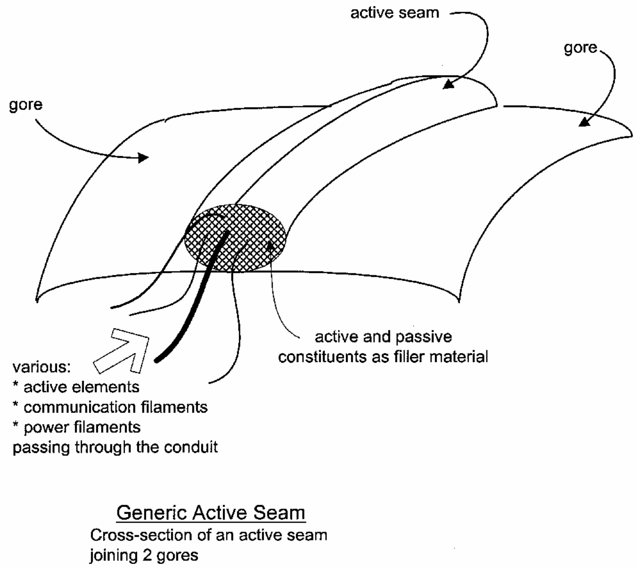

Fig. 3 Conceptual diagram of a generic active seam connecting two aperture gore segments.

Achieving precise shape of a gossamer aperture is complicated by that it must be maintained over a range of length scales derived from global and local shape considerations.[5,6] The bat analogy suggests a model of seam concept that can achieve both deployment and shape precision. A system of cartilaginouslike elements and soft tendonlike elements can be embedded in the seams. The former provides a network of deployment elements, whereas the latter aids in shape refinement. Together, they achieve the required shape precision. In developing models of such concepts, one will have to address a number of practical concerns, such as packageability, deployability, material and configuration compatibility, integration, weight/cost, and degree of surface precision achievable by the system.

As with all gossamer systems, packageability and deployability are of utmost concern; they are intimately entwined because one is the inverse process of the other. As a guide and point for comparison, recent developments in the technology of inflatables will serve as reference for developing models of the seam concepts. Deployment reliability and stability will have to be assured over the range of motion up to full deployment. Various concepts will be developed for mechanisms that initiate and followon the deployment of the seamed aperture. Elements that self-deploy passively on release of certain constraints are examples.

Prudent engineering encourages meeting design requirements as much as possible by passive means; hence, passive as well as active concepts must be considered. Configurations, such as active lap or tube seams, rigidizable or semirigidizable materials, local vs global control, hardwired vs noncontact communication, among others, must be considered. Interaction of the gores and seams with the aperture boundary needs to be taken into account. Figure 3 shows a generic active seam concept, showing essential elements to be considered.

Active Seam Simulation

To verify the concept of active seam manipulation to mitigate the deleterious effects of seams, a nonlinear finite element analysis using ABAQUS was performed. One-quarter of a gore/seam inflatable reflector was modeled, as seen in Fig. 4. Two seams are located at approximately 30 and 60 deg, respectively. Under pressurization, a

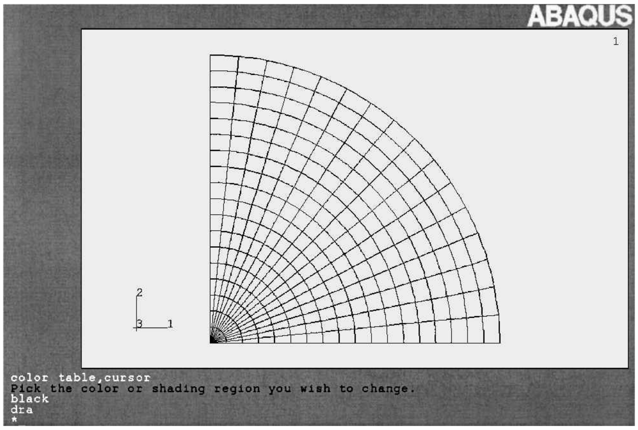

Fig. 4 Quarter symmetry ABAQUS finite element analysis model of an inflatable aperture; seams located at approximately 30 and 60 deg.

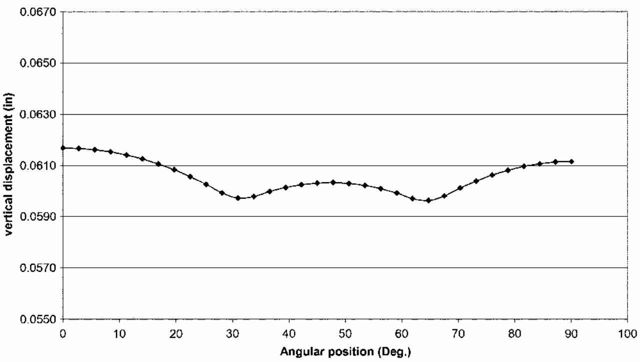

Fig. 5 Circumferential section (at arbitrary meridional position) showing the effects of the higher stiffness at the seams, as seen by the undulating topography (troughs at ~ 30 and 60 deg due to seams straining less than the gores). Vertical displacement vs angular position (when membrane pressurized to 0.1 Psi; without heating the seam ($E_c/E_s = 25$)($E_c = 1E + 07$ psi; $E_s = 4E + 05$ psi), double the original thickness.

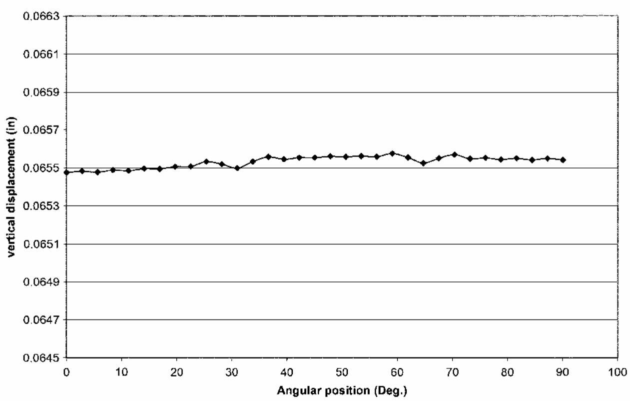

Fig. 6 Selectively expanding the seams only (by equivalent heating) essentially eliminates the undulation by matching the seam strain with the gore strain. Vertical displacement vs angular position when membrane pressurized to 0.1 psi; with heating the seam 49°F($E_c/E_s = 25$) ($E_c = 1E + 07$ psi; $E_s = 4E + 05$ psi), double the original thickness.

circumferential section of the deformed membrane clearly shows the effects of the nonuniform aperture stiffness by the undulating surface topography seen in Fig. 5. When the seams only are expanded, the undulations are almost completely removed (Fig. 6). In the model, we simply heat the seams, causing them to expand.

Lessons Learned from High-Altitude Ballooning

Until the late 1980s, the design of high-altitude balloons relied on analytical predictions that were based on the simple notions of classical membrane mechanics, which ignore heterogeneity and mechanical constitutive laws entirely. These predictions were in many instances grossly in error and had to be supplemented by experiments and scaling laws that used figures of merit rather than actual stresses for predicting the safety of a design. Later development using the nonlinear finite element code often in conjunction with some convergence enhancing artifices provided accurate predictions of the stress resultants in the balloon skin and the balloon load tapes.

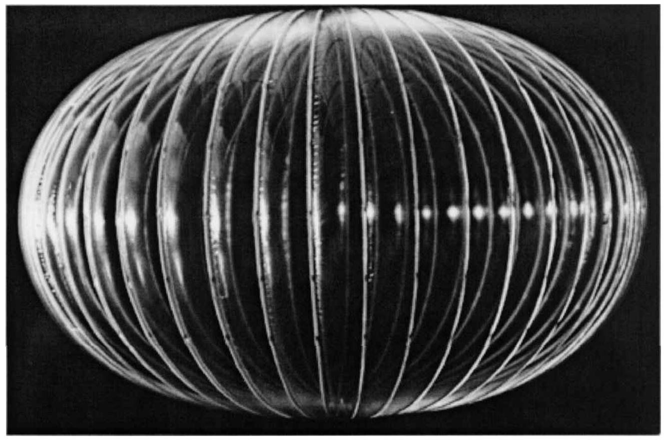

Fig. 7 Pumpkin-shape balloon.

The analysis of broader classes of thin skin pneumatic envelopes was enabled by incorporating tension field modeling and an akin feature that eases the modeling of structural lack of fit in a compliant structure. These features enable accurate predictions of the structural performance for tendon-reinforced membranes that are manufactured with excess skin. The response behavior of the so-called pumpkin-shape balloon was studied parametrically in 1998 (Fig. 7). This superpressure balloon type had been considered by a number of experimental investigators since 1977.

Although advantages of this design type were then qualitatively demonstrated, the lack of quantitative assessments prevented practical application. Findings of the analytical study on pumpkin-shape balloons redirected NASA's ultra-long-duration balloon (ULDB) program from the spherical design shape to a pumpkin-shape design. The skin material then under consideration for the spherical configuration appeared to be inadequate. This switch in design concept brought two benefits. The first benefit is a significant reduction in the required film strength to near that required for current zero-pressure balloons, and the second benefit is the ability to introduce into the design a measure of robustness that allows for fabrication imperfections.

The example of a parametric investigation[7] on pneumatic envelopes with varied goreseam architecture demonstrates the core idea of the analysis. This parametric investigation was performed to study the structural performance of a balloon design class that had been studied by several experimenters in the past, the pumpkin-shaped balloon. However, this balloon type had not been implemented in actual large-scale service flight vehicles. The experimenters' findings gathered from small test structures, though favorable, were primarily qualitative. The scant quantitative results from their experiments did not allow scaling; hence, they did not provide the confidence necessary for the development of large-scale flight vehicles. The analytical results of the parametric investigation not only confirmed the intuition of the experimenters, but it provided information on changes in the structural performance of this class of balloons as a function of mechanical properties of the skin and the tendons and of geometric aspects of the design and any built-in structural lack of fit. The analytic study shows that, in manipulating these aspects, the designer has the freedom to partition the load carrying function of skin and tendons at will. In the extreme, the structure can be made statically determinate with the tendons alone providing the global pressure-confining strength and the skin being reduced to the role of transferring the local pressure load to the tendons. Currently, a high-performance, superpressure, long-duration balloon that is under development by NASA and is to carry a 1750-kg load to an altitude of 35.1 km uses the pumpkin-shape balloon concept.

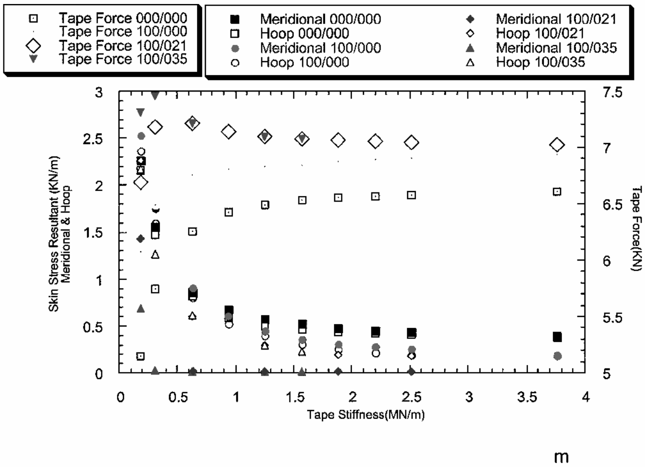

Fig. 8 Maximum values for stress resultants in pumpkin balloon classes 2 and 3; bulge radius is 1.0 m.

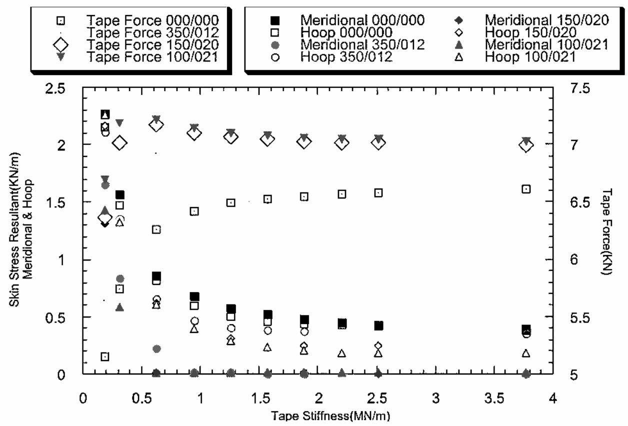

Fig. 9 Maximum values for stress resultants in pumpkin-shape balloon; selected configurations of class 3 with radii of 1.0, 1.5, and 3.5 m.

Earlier spherical superpressure balloons were capable of carrying only 50–100 kg to similar altitudes.

Figures 8 and 9 are taken from Ref. 7, and they represent but a small fraction of the balloons that have been analyzed in the parametric investigation; however, they allow us to exhibit all of the aspects that are the focus of this activity. There are almost 60 point designs plotted. Each point design is represented by three descriptors; these are the maximum stress resultants anywhere in the structure, that is, the maximum tape force and the maximum tension in the film in both the meridional and the hoop directions. The tape force is plotted on the right-hand scale, and the skin stress resultants are plotted on the left-hand scale. The fixed quantities in the design are the mechanical properties in the film, the size of the balloon, the number of gores, and the differential pressure across the pneumatic envelope. Their actual numbers are irrelevant for the discussion; it is the trends that are important that are associated with those quantities that are varied. All designs start with a basic shape that is determined from an equilibrium equation for a degenerate axisymmetric membrane that contains the pressure by a meridional force system only. This shape is referred to in ballooning as the natural shape. The tendons are assumed to follow the natural shape. They radiate out at equal angular intervals from the apex and nadir fittings. The balloon skin spans between adjacent gores.

The designs are grouped in three classes. The baseline class, designated by 000/000, is fabricated so that the skin of a gore fits exactly between two adjacent tendons (as laid out in the natural shape). The gores of an unpressurized yet somehow fully deployed balloon form developable surfaces. The other two classes are designed so that the unextended gores can bulge outward without experiencing extension. The gores are still made from flat sheets, and so the gore edges must be longer than the tendons. This mismatch is accommodated by a fabricated lack of fit at the gore edges. These design classes are designated by ###/000 and ###/###, where the number before the slash is the design bulge radius in millimeters. The class ###/000 has just sufficient gore material to accommodate the design bulge radius. The class ###/### is designed with constant lack of fit at the gore edge. That lack of fit is given in per mil equivalent strain.

Within each design class, the tape stiffness is varied from some low number to about 3.75 MN/m. A tendon stiffness of zero corresponds to the absence of tendons. In that case, the pressure envelope under constant internal pressure tends to deform toward a spherical shape being restrained from doing so by the tailoring of the pneumatic envelope. Large tensile stress resultants develop a short distance from the end fittings (the apex and nadir). Toward the equator, the stress resultants in the film reduce to some lower value. As the tendon stiffness increases, the stress-resultant peaks near the ends reduce, and the stress resultants in the central region reduce to a lower plateau. As the tendon stiffness increases further, the bulging gores in that central region in the vicinity of the equator assume a circular arc between the tendons, and the stress resultants in that region approach the product of pressure and bulge radius. The behavior so far described pertains to the left-hand side of the plots in Figs. 8 and 9. As the tendon stiffness increases further (going toward the right side of the plots), the peaks in the end regions diminish in amplitude and width and eventually come down to the plateau, as indicated in the plots by the asymptotic behavior of the peak stresses. One notes that the asymptotes for the designs with surplus gore width for designed-in bulge radius (###/### and ###/000) are significantly lower than those for the flat gores (000/000). Also, the peak stress resultants for smaller designed-in bulge radii are smaller than for the greater bulge radii. When increased meridional slackness is used with sufficient tendon stiffness, the film becomes slack in the meridional direction, the gores wrinkle (degenerate into tension-field behavior), and the meridional stress drops to zero. The elimination of the Poisson's effect from meridional stress also produces a longer bulge arc in the hoopwise direction, hence reduces the bulge radius and lowers the hoop stress. Therefore, in the presence of meridional wrinkling, the hoop stress has reached its asymptote.

In general, the stress resultants in the tendons for a particular design (a single set of data points) are nearly constant over the full length of the tendon. One can easily see in that case that a design with high tendon stiffness can be substituted by a design with a lower tendon stiffness and a length shortfall of the tendon with its corresponding increase in structural lack of fit at the gore seam tendon interface so that the effective secant stiffness of the two designs match.

This discussion demonstrates the flexibility in design options that is available to the designer of reinforced membranes. Different from rigid structures that require force fits that are usually associated with raised fabrication costs, in compliant structures lack of fit is relatively easy to achieve. When these options are exercised, the gains that can be achieved in structural efficiency can be significant.

Conclusions

In the near term at least, fabricating GS larger than about 10 m will likely require the seaming together of smaller parts. Rather than viewing this necessity as a disadvantage, this paper seeks to explore the advantages one can take with such an approach. Two such advantages are reviewed: 1) the possibility of making the seams active, providing for both deployment and shape control, and 2) the ability to modify the stress distribution in the membrane through manipulation of the gore and seam curvatures.

The latter design scheme is applicable to other large-scale lightweight structures that with low areal weight are required to span large surfaces and whose function is to transfer transverse pressure load into the plane of the compliant structure and then to its boundary. The structural tradeoff is between the required film strength and the strength and number of tendons. The intent is to carry the local pressure load over only a short span to the load tendons and to let the tendons transfer that load over a long span to the boundary of the compliant structure. Gains in a reduced strength requirement for the skin are only made when the radius of curvature of the skin in the plane perpendicular to the tendons is significantly smaller than the radius of curvature of the arc that is assumed by the tendons. In the superpressure balloon design of the ULDB, the respective radii of curvature are roughly two decades apart.

Acknowledgments

The authors wish to express their appreciation to Joseph Bar-Cohen and Moktar Salama of the Jet Propulsion Laboratory for their contributions to this paper.

References

[1]Chmielewski, A. B., and Jenkins, C. H., "Gossamer Structures: Space Membranes, Inflatables and Other Expandables," *Structures Technology for Future Aerospace Systems*, edited by A. K. Noor, Vol. 188, Progress in Astronautics and Aeronautics, AIAA, Reston, VA, 2000, Chap. 5, pp. 201–268.

[2]Salama, M., and Jenkins, C. H., "Intelligent Gossamer Structures: A Review of Recent Developments," AIAA Paper 2001-1196, April 2001.

[3]Jenkins, C. H., and Faisal, S. M., "Thermal Load Effects on Precision Membranes," *Journal of Spacecraft and Rockets*, Vol. 38, No. 2, 2001, pp. 207–211.

[4]Jenkins, C. H., and Vinogradov, A., "Active Polymers for Space Inflatables: Properties and Applications," Inst. of Electrical and Electronics Engineers, IEEE Aerospace Conf. [CD-ROM], March 2000.

[5]Jenkins, C. H., "Shape Control of Precision Gossamer Apertures," *Electroactive Polymer Actuators*, edited by Y. Bar-Cohen, Society of Photo-Optical Instrumentation Engineers, Bellingham, WA, Chap. 20, pp. 595–611.

[6]Jenkins, C. H., and Kalanovic, V. D., "Issues in Control of Space Membrane/Inflatable Structures," Inst. of Electrical and Electronics Engineers, IEEE Aerospace Conf. [CD-ROM], March 2000.

[7]Schur, W. W., "Analysis of Load Tape Constrained Pneumatic Envelopes," AIAA Paper 99-1526, 1999.

J. Lassiter
Guest Editor